PROCEEDINGS OF SCIENCE

New measurements of transverse spin asymmetries at COMPASS

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The recent developments in the description of the 3D structure of the nucleon have highlighted the relevance of SIDIS measurements with transversely polarized nucleons. The phenomenological analyses have also highlighted how the scarcity of SIDIS data collected with neutron or deuterium targets limits the knowledge of the parton distribution functions, in particular for the d quark.
In the year 2022, the COMPASS experiment at CERN took data using a transversely polarised deuteron target and a 160 GeV muon beam at CERN, to balance the existing proton target data. Detailed studies had shown how those data would lead to significant progress in the knowledge of the transversity distributions.
First preliminary results for the Collins and Sivers asymmetries from part of the 2022 data have already been produced, they are in line with expectations and are shown here for the first time.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

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COMPASS is a fixed target experiment that took data from 2002 to 2022 at the M2 beam line of the CERN SPS, covering a broad hadron physics programme. A large fraction of the data taking was dedicated to the study of the nucleon structure by measuring different processes, namely semi-inclusive deep inelastic lepton–nucleon scattering (SIDIS), pion–induced Drell–Yan process, Deeply Virtual Compton Scattering and exclusive vector meson production.

This talk is dedicated to the COMPASS measurements of SIDIS off transversely polarised proton and deuteron targets. First low statistics measurements with the deuteron (^{6}LiD) target were performed at the very beginning of the data taking, in the years 2002 to 2004, with a reduced geometrical acceptance of the spectrometer, and a full SPS year of data taking took place the last year of running, in 2022. The data with the proton (NH_3) were collected in 2007 and 2010, after the important spectrometer upgrade of 2005, when in particular the new large–acceptance solenoid magnet of the polarised target system was installed.

The relevance of the SIDIS measurements with transversely polarised targets is clear when considering the present description of the nucleon structure in terms of transverse momentum dependent (TMD) parton distribution functions (PDFs) and the expression of the SIDIS cross section. In the present theoretical framework [1–3] at leading twist the longitudinal and intrinsic transverse motion of partons inside a hadron, as well as the parton and nucleon spins and their correlations, are encoded in eight transverse momentum dependent (TMD) parton distribution functions (PDFs). Only three of these survive the integration over the quark transverse momentum: the number distributions f_1, the helicity distributions g_1, and the transversity distributions h_1. Transversity [4] is the analog of the helicity distribution g_1 in the case of transversely polarised nucleons, namely it is the difference of the number of quarks with spin direction parallel and the number of quarks with spin direction opposite to the nucleon spin in a transversely polarised nucleons. It has properties that are different from those of g_1. In particular, h_1 is chiral-odd and not directly observable in inclusive DIS but only in processes where it is coupled with another chiral-odd function. The relevance of the transversity PDFs is also related to the fact that its integrals for the valence u and d quarks give the nucleon tensor charge, a fundamental property of the nucleon that can also be calculated in lattice QCD [5, 6].

In the SIDIS cross section [3], several modulations in different azimuthal angles appear. The amplitudes of some of them, at leading order in perturbative QCD, can be written in terms of convolutions over transverse momenta of TMD PDFs and fragmentation functions (FFs). The measurement of the so-called azimuthal asymmetries, proportional to these amplitudes, gives thus access to the TMD PDFs when using independent information on the FFs. An important feature of SIDIS measurements is that the use of different targets (proton and neutron or deuteron) and the identification of the final state hadrons allow to access the PDFs of the different quark flavours.

When the target nucleon is transversely polarised, five (eight in case of polarised lepton beam) different spin-dependent azimuthal asymmetries are allowed, four of them related to TMD PDFs. The so-called Collins asymmetry $A_{\rm Coll}$ is proportional to the convolution of the transversity distribution with the Collins FF $H_1^\perp$ which describes the hadronisation of transversely polarised quarks. Independent information on $H_1^\perp$ is obtained from the measurement of azimuthal asymmetries in $e^+e^- \rightarrow hadrons$. A second one, the Sivers asymmetry $A_{\rm Siv}$, contains the convolution of the spin-averaged FF D_1 and the Sivers function, the most famous and discussed TMD PDF, which encodes the correlation between the transverse spin of the nucleon and a parton intrinsic transverse

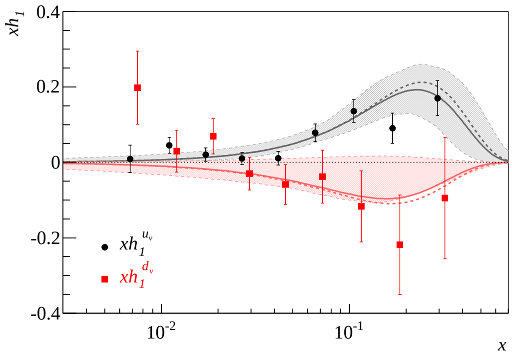

Figure 1: Valence transversity distributions, $xh_1^{u_v}$ (black circles) and $xh_1^{d_v}$ (red squares) compared to the corresponding distributions extracted in Ref. [15] (curves and error bands). Figure from Ref. [12]

momentum [7].

In this context, about 25 years ago the HERMES and COMPASS Collaborations proposed to measure transverse spin effects in SIDIS. HERMES at DESY used a 27 GeV electron beam and a proton target while COMPASS started the data taking with the deuteron target. Those measurements were real milestones finding Collins and Sivers asymmetries clearly different from zero for the proton and compatible with zero for the deuteron [8, 9]. They demonstrated the correctness of recent conjectures, namely that the transversity functions, the Collins FFs and the Sivers functions are different from zero, and that there is cancellation between the contributions of the u and d quarks.

As soon as these first SIDIS data were available, phenomenological analyses allowed for the extraction of the first moments of the Sivers functions that turned out to be different from zero and of opposite sign for the u and d valence quarks. When the Belle e^+e^- data became available [10], also the transversity distributions were obtained. The extracted values of $h_1^{u_v}$ turned out to be clearly different from zero, while the values of $h_1^{d_v}$ were found to be negative but with large statistical uncertainties due to the poor precision of the deuteron data. In the following, more refined results were published by HERMES, and also COMPASS took high statistics data with the transversely polarised proton target in 2007 and, for the full year, in 2010. The first low statistics COMPASS data collected with the deuteron target stayed the only existing ones. A measurement with a transversely polarised neutron (^{3}He) target and a 5.9 GeV electron beam was performed at JLab [11] but again with limited statistics, and still today the d quark transversity, as well as the other TMD PDFs, is poorly known. As an example, fig. 1 shows the transversity functions of u_v and d_v extracted point-by-point [12] using the COMPASS proton and deuteron measurements of the Collins asymmetry [13, 14] and the Belle measurements. The curves and the bands show the results of a phenomenological analysis [15] which includes also the HERMES proton results and the Soffer bound. The statistical precision on $h_1^{d_v}$ improves only when including in the analyses the pp results, thus limiting the possibility of testing the universality of the PDFs, or theory inputs, like the lattice QCD results.

As a conclusion, it became clear that new SIDIS measurements with transversely polarised

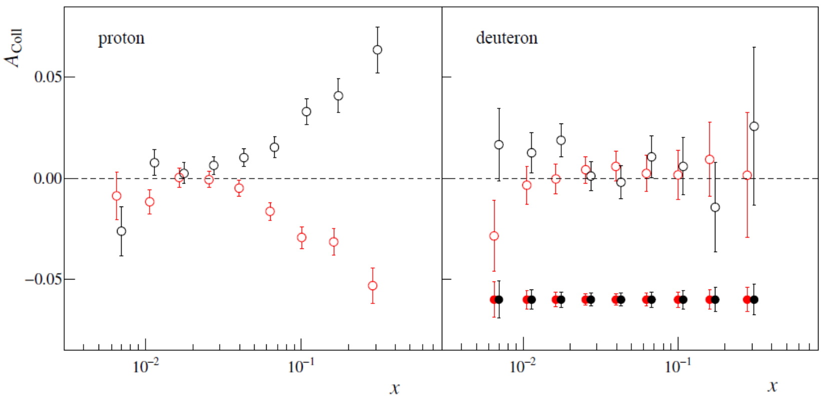

Figure 2: The Collins asymmetry obtained from all the COMPASS proton data [14] (left panel) and from the 2002-2004 deuteron data [13] (right panel) as a function of x (open points). The red (black) points refer to positive (negative) hadrons. The full points at −0.06 in the right plot show the expected statistical uncertainties from the proposed deuteron run.

neutron or deuteron targets were mandatory, and only COMPASS could perform those measurements. In 2018, the Collaboration proposed one SPS year (about six months) of data taking in the same conditions as the 2010 proton run using the transversely polarised deuteron target. Detailed studies were performed [16], and it was shown that, with only small modifications of the spectrometer, the transverse spin asymmetries could be measured with statistical uncertainties about 0.6 times smaller than those of corresponding measurements performed using the 2010 data, namely statistical uncertainties 2 (at small x) to 4 times smaller than those of the existing deuteron results. As an example, in the right panel of fig. 2 the measured $A_{\rm Coll}$ for positive and negative hadrons from the 2002-2004 deuteron data (open points) [13] are compared with the projected uncertainties of the proposed measurement (full points at −0.6). The left panel shows the same $A_{\rm Coll}$ asymmetries obtained from the 2007 and 2010 proton data [14].

The impact of the proposed measurements was investigated in particular for the transversity and the tensor charge [16], and it is summarised in the following. We used the point-by-point extraction of Ref. [12], with the same unpolarised PDFs and FFs and the same analysing power from the Belle data. The $A_{\rm Coll}$ results from the 2010 proton data for positive and negative hadrons have been used, assuming that all the charged hadrons are pions. When using all the existing measured asymmetries with deuteron target, namely the COMPASS results from the 2002-2004 data set, the transversity values shown in the left panel of fig. 3 are obtained. The central curves are simple fits to the transversity values and the bands give the 68% and 90% confidence regions obtained from replicas of the Collins asymmetry measurements. The right panel of fig. 3 shows the transversity values and error bars obtained replacing the uncertainties of $A_{\rm Coll}$ for deuteron with those expected from the proposed measurement. The gain in precision for the d-quark ranges from a factor of 2 at small x to more than a factor of 4 at large x, and the gain is also noticeable for the u-quark. In addition to the reduction of the statistical uncertainties, it is important to note that the estimated values of $xh_1^{u_v}$ and $xh_1^{d_v}$ are correlated, since they are obtained in each x bin as linear functions of the same four measured asymmetries. With the present unbalanced statistics of proton and deuteron data, we have evaluated a quite large correlation coefficient (+0.4 at small x, +0.8 in the highest x bin). When

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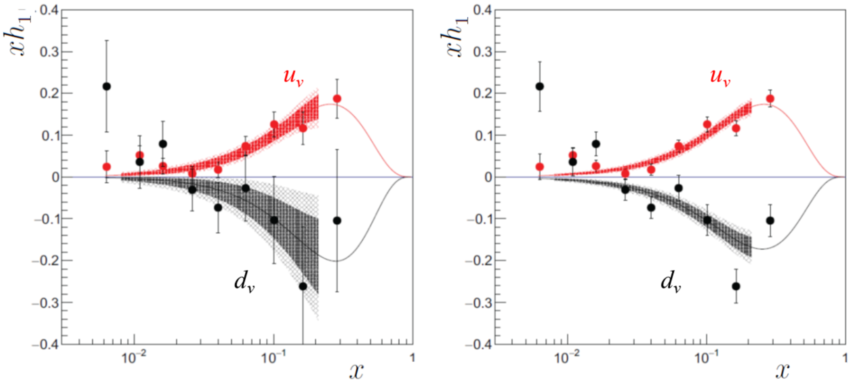

Figure 3: Left: $xh_1^{u_v}$ (red dots) and $xh_1^{d_v}$ (black dots) obtained using the A_{Coll} results from the 2010 proton data and the 2002-2004 deuteron data. The curves are fits with a simple x-dependent function and the bands show the 68% and 90% confidence regions. Right: the same, when replacing the uncertainties of the deuteron Collins asymmetry with the projected uncertainties of the proposed measurement.

using the projected uncertainties of the deuteron asymmetries, the correlation coefficient becomes smaller in absolute value and negative, ranging between −0.2 and −0.3.

The projected statistical uncertainties on the transversity distributions have then been used to evaluate the impact of the proposed measurement on the evaluation of the tensor charges in the range $0.008 < x < 0.210$ (Ω_x). The statistical uncertainties on the truncated tensor charges $\delta q = \int_{\Omega_x} dx[h_1^q(x) - h_1^{\bar{q}}(x)]$ with $q = u, d$ and $g_T = \delta u - \delta d$ have been evaluated both by numerical integration over the x bins and by integrating the curves of fig. 3 ,obtaining very close results. The uncertainty on δd turned out to be considerably reduced, from 0.110 to 0.043. Also the knowledge of δu would improve, decreasing the statistical error from 0.036 to 0.025. For the tensor charge g_T the uncertainty goes from 0.093 to 0.054, namely almost a factor of two.

The proposal was approved by CERN and the COMPASS Collaboration took data from September to November 2022 with the 160 GeV/c μ^+ beam, the transversely polarised ^{6}LiD target, and an experimental apparatus very similar to the one used in 2010.

No major problem occurred in that period, neither with SPS beam delivery nor with the polarised target system and the COMPASS spectrometer operation. First data quality tests, detector alignment procedure and preliminary event reconstruction were performed in real time to identify possible problems. At the end of the data taking, the collected statistics was in line with expectations. In September 2022 all data were processed and standard quality tests and systematic studies were performed, confirming that the uncertainties on the transverse spin asymmetries from the 2022 data were in agreement with what was anticipated in the proposal. Final systematic studies have been performed for the Collins and Sivers asymmetries, for positive and negative hadrons, measured from about half of the 2022 data sample and the results are shown here for the first time.

The closed points in fig. 4 shows the preliminary results for A_{Coll} from about half of the 2022 deuteron data as a function of x, z, and P_{T}, the transverse momentum of the hadron with respect to the virtual photon direction, for positive (top) and negative (bottom raw) hadrons. The open points show the COMPASS results from the 2002-2004 data [13]. As can be seen, the improvement is

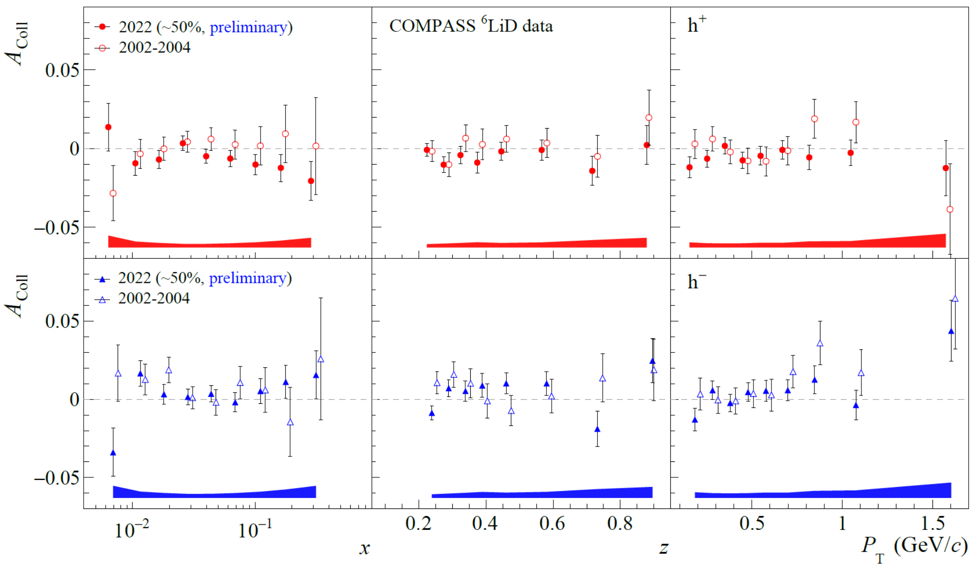

Figure 4: A_{Coll} for positive (top raw) and negative (bottom raw) hadrons vs x, z and P_T. The full points are the new preliminary results from part of the 2022 deuteron data, the open points are the results from the 2002-2004 deuteron data [13].

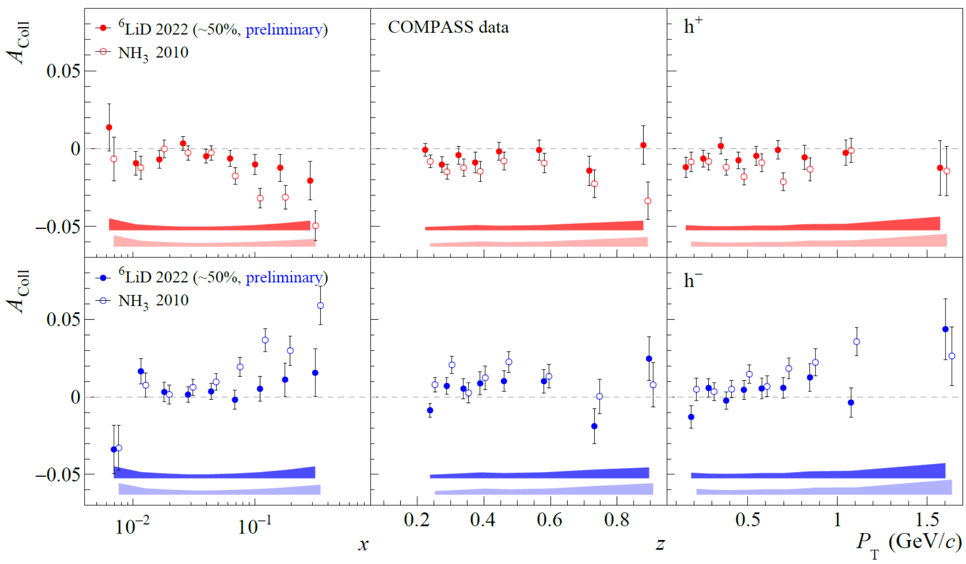

Figure 5: A_{Coll} for positive (top raw) and negative (bottom raw) hadrons vs x, z and P_T , The full points are the new preliminary results from part of the 2022 deuteron data (the same as in fig. 4), the open points show the results from the 2010 proton data [14].

impressive, even using only part of the 2022 data. Also, while the previous results do not show any specific trend, and the data points were compatible with zero within the statistical uncertainties, the present results show hints for negative (positive) values at large x for positive (negative) hadrons. The x dependence is similar to that of A_{Coll} for protons, as can be seen in fig. 5, where the new results for deuteron are compared with the COMPASS results for proton. As expected, the statistical uncertainties for proton and deuteron are now about the same.

The corresponding results for A_{Siv} on deuteron vs x, z, and P_T are shown as closed points in fig. 6. The top (bottom) plots give the asymmetries for positive (negative) hadrons. The open points are the COMPASS results from the 2002-2004 data. As in the Collins case, the precision of the new measurement is higher by about a factor of three. Despite the relevant improvement in the precision of the measurement, the Sivers asymmetries are again compatible with zero, supporting to a large extent the cancellation of the contributions of the u and d quarks.

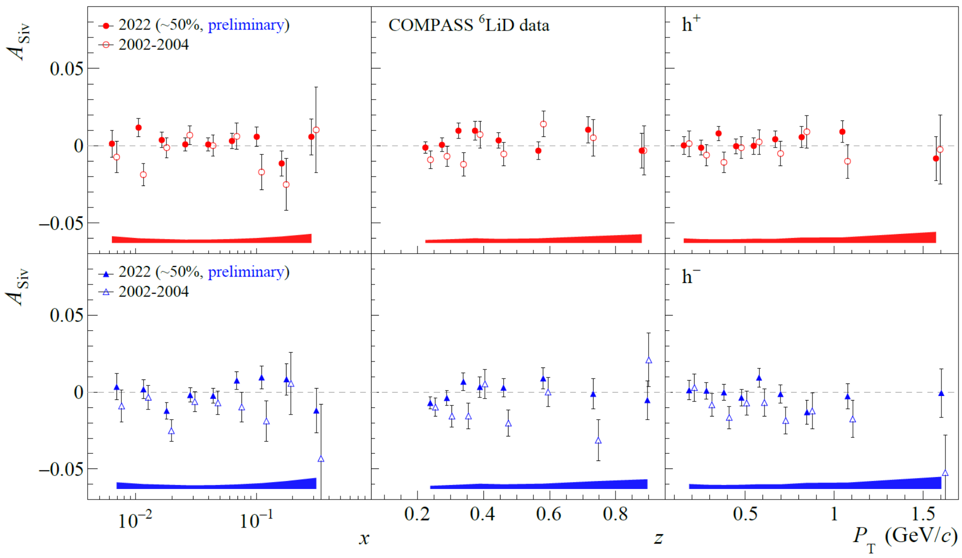

Figure 6: A_{Siv} for positive (top raw) and negative (bottom raw) hadrons vs x, z and P_T , The full points are the new preliminary results from part of the 2022 deuteron data, the open points are the results from the 2002-2004 deuteron data [13].

To summaries, the COMPASS Collaboration has produced the first results from part of the SIDIS data collected in 2022 using the transversely polarised deuteron target. The new measurements of the Collins and the Sivers asymmetries are characterized by a remarkable improvement in precision, and they represent a new important input for phenomenological analyses. The same improvements are expected for the other measurements, like the di-hadron asymmetries. The 2022 data will also allow for the other measurements of transverse spin asymmetries already performed by COMPASS using the proton data [17] and that could not be performed using the previous low-statistics and reduced acceptance deuteron data. In conclusion, the 2022 data taking has been a success, it allowed completing the COMPASS exploratory programmer to study transverse spin effects in SIDIS, collecting data which will stay unique for several years, while waiting for the new experiments at JLab and EIC.

References

[1] A. Kotzinian, *Nucl. Phys. B* **441** (1995) 234, arXiv:hep-ph/9412283.

[2] P. J. Mulders and R. D. Tangerman, *Nucl. Phys. B* **461** (1996) 197, arXiv:hep-ph/9510301. [Erratum-ibid. *B* **484** (1997) 538].

[3] A. Bacchetta *et al.*, *JHEP* **0702** (2007) 093, arXiv:hep-ph/0611265 [hep-ph].

[4] J. P. Ralston and D. E. Soper, *Nucl. Phys. B* **152** (1979) 109.

[5] J.-W. Chen, S. D. Cohen, X. Ji, H.-W. Lin and J.-H. Zhang, *Nucl. Phys. B* **911** (2016) 246, arXiv:1603.06664 [hep-ph].

[6] T. Bhattacharya *et al.*, *Phys. Rev. D* **94** (2016) 054508, arXiv:1606.07049 [hep-lat].

[7] D. W. Sivers, *Phys. Rev. D* **41** (1990) 83.

[8] HERMES Collaboration, A. Airapetian *et al.*, *Phys.Rev.Lett.* **94** (2005) 012002, arXiv:hep-ex/0408013 [hep-ex].

[9] COMPASS Collaboration, V. Y. Alexakhin *et al.*, *Phys. Rev. Lett.* **94** (2005) 202002, arXiv:hep-ex/0503002.

[10] BELLE Collaboration, R. Seidl *et al.*, *Phys. Rev. D* **78** (2008) 032011, arXiv:0805.2975 [hep-ex].

[11] Jefferson Lab Hall A Collaboration, X. Qian *et al.*, *Phys. Rev. Lett.* **107** (2011) 072003, arXiv:1106.0363 [nucl-ex].

[12] A. Martin, F. Bradamante and V. Barone, *Phys. Rev. D* **91** (2015) 014034, arXiv:1412.5946 [hep-ph].

[13] COMPASS Collaboration, E. S. Ageev *et al.*, *Nucl. Phys. B* **765** (2007) 31, arXiv:hep-ex/0610068.

[14] COMPASS Collaboration, C. Adolph *et al.*, *Phys. Lett. B* **717** (2012) 376, arXiv:1205.5121 [hep-ex].

[15] M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia and A. Prokudin, *Phys. Rev. D* **87** (2013) 094019, arXiv:1303.3822 [hep-ph].

[16] COMPASS Collaboration, K. Augsten *et al.*, *SPSC-P-340-ADD-1, CERN–SPSC–2017–034* (2018) .

[17] COMPASS Collaboration, M. G. Alexeev *et al.*, *Nucl. Phys. B* **940** (2019) 34–53, arXiv:1809.02936 [hep-ex].

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